



# 8 Observations of Atmospheric Carbon Dioxide and Methane

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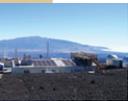
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## KEY FINDINGS

1. Global concentrations of carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) have increased almost linearly since the *First State of the Carbon Cycle Report* (CCSP 2007; see Figure 8.1, p. 339). Over the period 2004 to 2013, global growth rates estimated from the National Oceanic and Atmospheric Administration's marine boundary layer network average  $2.0 \pm 0.1$  parts per million (ppm) per year for CO<sub>2</sub> and  $3.8 \pm 0.5$  parts per billion (ppb) per year for CH<sub>4</sub>. Global mean CO<sub>2</sub> abundance as of 2013 was 395 ppm (compared to preindustrial levels of about 280 ppm), and CH<sub>4</sub> stands at more than 1,810 ppb (compared to preindustrial levels of about 720 ppb) (*very high confidence*).
2. Inverse model analyses of atmospheric CO<sub>2</sub> data suggest substantial interannual variability in net carbon uptake over North America. Over the period 2004 to 2013, North American fossil fuel emissions from inventories average  $1,774 \pm 24$  teragrams of carbon (Tg C) per year, partially offset by the land carbon sink of  $699 \pm 82$  Tg C per year. Additionally, inversion models suggest a trend toward an increasing sink during the period 2004 to 2013. These results contrast with the U.S. land sink estimates reported to the United Nations Framework Convention on Climate Change, which are smaller and show very little trend or interannual variability.
3. During most of the study period covered by the *Second State of the Carbon Cycle Report* (2004 to 2012), inverse model analyses of atmospheric CH<sub>4</sub> data show minimal interannual variability in emissions and no robust evidence of trends in either temperate or boreal regions. The absence of a trend in North American CH<sub>4</sub> emissions contrasts starkly with global emissions, which show significant growth since 2007. Methane emissions for North America over the period 2004 to 2009 estimated from six inverse models average  $66 \pm 2$  Tg CH<sub>4</sub> per year. Over the same period, CH<sub>4</sub> emissions reported by the U.S. Environmental Protection Agency equate to a climate impact of 13% of CO<sub>2</sub> emissions, given a 100-year time horizon.

*Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.*

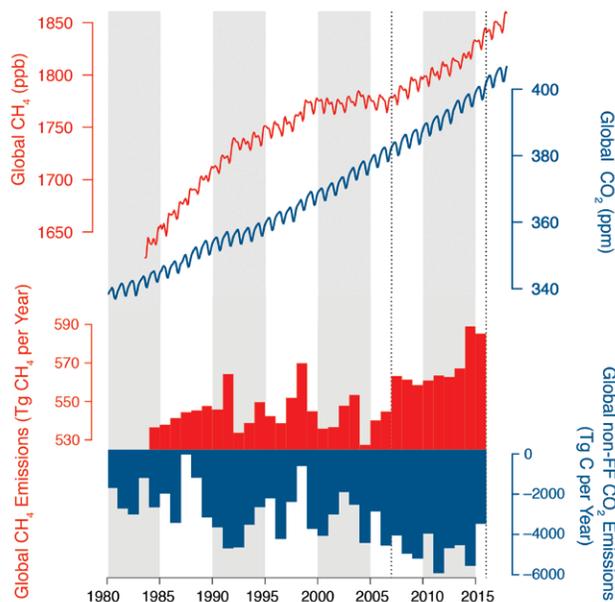
## 8.1 Introduction

Atmospheric carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) are the primary contributors to anthropogenic radiative forcing. Atmospheric concentration measurements of these two species provide fundamental constraints on sources and sinks, quantities that need to be monitored and understood in order to guide societal responses to climate change. These atmospheric observations also have provided critical insights into the global carbon cycle and carbon stocks and flows among major reservoirs on land and in the ocean. This chapter discusses atmospheric CO<sub>2</sub> and CH<sub>4</sub> measurements and their use in inverse modeling.

After decades of steady growth in anthropogenic carbon emissions associated with fossil fuel consumption, global emissions began to stabilize in

2014 and 2015 (BP 2016). Global emissions nearly doubled from 5,000 teragrams of carbon (Tg C) per year in 1980 to around 10,000 Tg C per year in 2015. In North America, emissions recently have been decreasing: in Canada from 151 to 141 Tg C per year between 2004 to 2013, and in the United States from 1,570 to 1,407 Tg C per year over the same time period (Boden et al., 2017). Nevertheless, the global atmospheric CO<sub>2</sub> concentration has passed the 400 parts per million (ppm) milestone (a part per million represents the mole fraction of CO<sub>2</sub> in dry air and is equivalently expressed as  $\mu\text{mol per mol}$ ). Given the long lifetime of atmospheric CO<sub>2</sub>, this global burden will continue to rise as long as net emissions remain positive.

The global atmospheric growth rate of CO<sub>2</sub> has averaged around half the rate of CO<sub>2</sub> input from fossil fuel combustion over the last 50 years, rising



**Figure 8.1. Global Monthly Mean Concentrations of Methane (CH<sub>4</sub>; red line) and Carbon Dioxide (CO<sub>2</sub>; blue line) and Global Annual Emissions of CH<sub>4</sub> (red bars) and Nonfossil Fuel Annual Emissions of CO<sub>2</sub> (blue bars).** Global CH<sub>4</sub> and CO<sub>2</sub> concentrations (in parts per billion [ppb] and parts per million [ppm], respectively) are from the National Oceanic and Atmospheric Administration’s Marine Boundary Layer product. Methane emissions were generated from annual growth rates of marine boundary layer CH<sub>4</sub>, assuming a CH<sub>4</sub> lifetime of 9.1 years. Carbon dioxide emissions were generated from annual growth rates of marine boundary layer CO<sub>2</sub>, converted to emissions using a factor of 2,128 teragrams of carbon (Tg C) per year per ppm and removing anthropogenic fossil fuel emissions. From 1980 to 2016, these global fossil fuel emissions grew steadily from about 5,000 Tg C per year to about 9,200 Tg C per year (Boden et al., 2017). Dotted vertical lines in 2007 and 2016 represent approximate reference times for publication of the first and second *State of the Carbon Cycle* reports.

from less than 1 ppm per year in the early 1960s to around 2.5 ppm per year between 2010 and 2015 (see Figure 8.1, this page; Ballantyne et al., 2015). Although the growth rate varies substantially from year to year, mainly in response to the El Niño–Southern Oscillation (Bacastow 1976; Sarmiento et al., 2010), the trend in net CO<sub>2</sub> absorption by the terrestrial biosphere and the ocean has increased from around 2,000 Tg C per year in 1960 to nearly

5,000 Tg C per year in 2015 (see Figure 8.1, this page; Ballantyne et al., 2015). Although the total sink is well constrained, now limited mainly by the ~5% to 10% uncertainty on global fossil fuel emissions, its partitioning between land and ocean and on land between continents is still uncertain. Accordingly, there is no consensus on the fraction of the global sink in North America, although almost all inventory, biospheric model, and atmospheric studies show it to be a sink (King et al., 2015).

The global abundance of CH<sub>4</sub> grew significantly from 1984 to 1996, but between 1997 and 2006 there was no significant change in global burden (see Figure 8.1, this page). This quasi-asymptotic behavior can be explained as an approach to steady-state concentrations (Dlugokencky et al., 1998). The balance between surface sources and atmospheric chemical loss, which is mainly due to oxidation by hydroxyl radicals, can be explained by constant emissions and a constant atmospheric CH<sub>4</sub> lifetime. For the emissions calculations reported in this chapter, a value of 9.1 years was used for this lifetime (Montzka et al., 2011). Indeed, global net emissions exhibited variability but no significant trend between 1984 and 2006 (Dlugokencky et al., 2011; see Figure 8.1, this page). After 2007, however, global CH<sub>4</sub> abundance began to rise rapidly (e.g., Dlugokencky et al., 2009; Nisbet et al., 2016), implying an increase in global emissions from 541 ± 8 Tg CH<sub>4</sub> per year (1999 to 2006) to 569 ± 12 Tg CH<sub>4</sub> per year (2008 to 2015). Emissions in 2014 and 2015 are particularly large, with a mean of 587 ± 3 Tg CH<sub>4</sub> per year. Analysis of trends in the <sup>13</sup>C:<sup>12</sup>C content of CH<sub>4</sub> (δ<sup>13</sup>C) indicates that, at global scales, the rise since 2007 resulted predominantly from changes in microbial emissions (e.g., wetlands, livestock, and agriculture) and not fossil fuel–related emissions (Schaefer et al., 2016; Schwietzke et al., 2016). Moreover, because the recent CH<sub>4</sub> trend displays no significant meridional gradient, much of this new emissions increment likely originated in the tropics (Nisbet et al., 2016) and not in the northern midlatitudes.

Global total emissions of CO<sub>2</sub> and CH<sub>4</sub> are well constrained by available atmospheric measurements;



however, using these measurements to attribute to sources and sinks (e.g., fossil emissions versus terrestrial biosphere uptake) or partitioning between land and ocean regions remains difficult. In fact, even at smaller scales (i.e., continental regions as large as North America), substantial uncertainty remains about net contributions by terrestrial and aquatic ecosystems. The ability to use CO<sub>2</sub> and CH<sub>4</sub> time and space gradients to constrain North American sources and sinks is limited by current knowledge of atmospheric mixing and by the time and space density of calibrated observations (see Section 8.6, p. 349).

## 8.2 Historical Context

From the late 1950s through mid-1990s, measurements of atmospheric CO<sub>2</sub> and CH<sub>4</sub> concentrations were mostly targeted at understanding variations in “background” marine air, remote from the complex signals found over continents. Motivated largely by the finding of Tans et al. (1990) that Northern Hemisphere extratropical land regions were very likely a significant CO<sub>2</sub> sink, new attention was placed on understanding the role played by terrestrial ecosystems. New measurement sites were established on land, with an emphasis on platforms extending well into the daytime planetary boundary layer or higher, in an attempt to capture signals of regional (approximately 1,000 km) surface exchange (Gloor et al., 2001). This effort included observations on towers extending far above the ecosystem canopy (typically >300 m above ground level) and from light aircraft flying well into the free troposphere (typically >6 km above sea level).

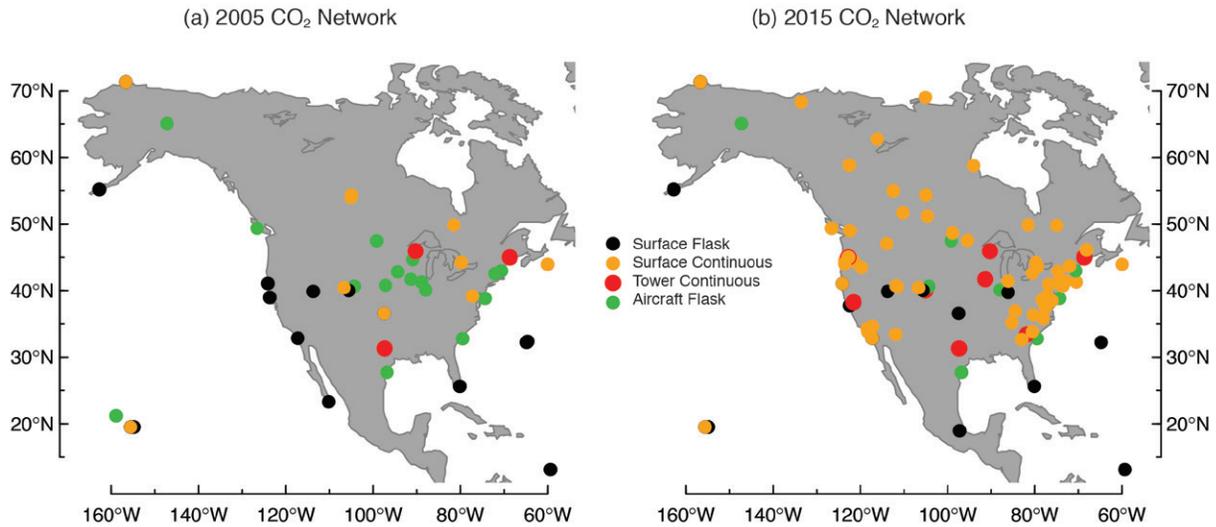
The availability of calibrated, comparable observations of atmospheric CO<sub>2</sub> mole fractions on a common scale has made it possible to estimate surface exchange via inversion of atmospheric transport. Studies including Enting and Mansbridge (1991), Fan et al. (1998), and the ensuing Atmospheric Tracer Transport Model Intercomparison Project (TransCom) model intercomparisons (e.g., Baker et al., 2006; Gurney et al., 2002) reported widely ranging values of mean sinks for continental-scale

land regions. These results demonstrated that, in the face of highly variable surface fluxes, uncertainties and biases in atmospheric transport models (e.g., Stephens et al., 2007), coupled with the sparseness of available observations, render the estimation of mean surface fluxes strongly underconstrained. In the context of a common estimation methodology, interannual variability in surface fluxes can be strikingly coherent between inversion models (Baker et al., 2006; Peylin et al., 2013), suggesting that standing biases in transport models may drive differences in the mean flux estimated by global inverse models.

At the time of the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007), there was agreement within large uncertainty bounds between “bottom-up” estimates from terrestrial biomass inventories and “top-down” atmospheric studies (Pacala et al., 2001; see Ch. 2 and Ch. 3 in SOCCR1) on the size of the terrestrial CO<sub>2</sub> sink in North America. Atmospheric inverse modeling was discussed in SOCCR1, but the final fluxes reported for North America excluded estimates from those techniques. These estimates were brought together for the first time at the continental scale for the North American Carbon Program (NACP) interim regional synthesis project (Hayes et al., 2012; Huntzinger et al., 2012).

## 8.3 Current Understanding of Carbon Fluxes and Stocks

The global average atmospheric CO<sub>2</sub> concentration in 2015 of about 401 ppm (see Figure 8.1, p. 339) is roughly 20 ppm (5%) higher than in 2007. The anthropogenic excess of CO<sub>2</sub>—the concentration in the atmosphere above the preindustrial level of about 280 ppm—has grown by 20% in just the 8 years since 2007. The 2015 global average concentration of CH<sub>4</sub> was about 1,833 parts per billion (ppb), which is 3% higher than in 2007 (a 5% increase in the anthropogenic excess).



**Figure 8.2. Growth of the North American Carbon Dioxide (CO<sub>2</sub>) Monitoring Network from (a) 2005 to (b) 2015.** Many National Oceanic and Atmospheric Administration aircraft sites were terminated after 2005. Unlike “surface” sites, “tower” sites generally have inlets 100 m to 400 m above the surface and sometimes sample air above the planetary boundary layer. About 90% of both tower and surface sites also report methane measurements.

### 8.3.1 Advances in Atmospheric Measurements and Platforms

#### Surface Networks

The observation network for atmospheric CO<sub>2</sub> and CH<sub>4</sub> has grown dramatically since SOCCR1 (see Figure 8.2, this page). Networks are now run by 1) governmental institutions such as the National Oceanic and Atmospheric Administration (NOAA), Environment and Climate Change Canada, U.S. Department of Energy, and California Air Resources Board; 2) research institutions including the National Center for Atmospheric Research (NCAR) and National Ecological Observatory Network (NEON); 3) universities such as Scripps Institution of Oceanography, The Pennsylvania State University, Oregon State University, and Red Universitaria de Observatorios Atmosfericos in Mexico; and 4) corporations (e.g., Earth Networks). Platforms and measurement techniques for observing greenhouse gas (GHG) distributions also have grown and become more diverse. In 2005, the North American CO<sub>2</sub> and CH<sub>4</sub> surface network mainly consisted of weekly surface flask–air

sampling at a handful of sites and continuous observations at several observatories and three tall towers (see Figure 8.2, this page). Sustained records are now available from many more towers, especially those of intermediate (~ 100 m) height. As the density of the North American GHG measurement network has grown, the emissions sensitivity of observations has moved from hemispheric scales (using background marine boundary layer observations), to regional scales (using tower and aircraft observations), and, more recently, to local scales from urban networks and oil and gas measurement campaigns. These new *in situ* measurements of CO<sub>2</sub> and CH<sub>4</sub> (see Figure 8.2, this page) have been enabled by better availability of higher-precision, stable laser spectroscopic analyzers that require less-frequent calibration, although traceability to a common CO<sub>2</sub> reference scale is critical for this collection of networks to be unified. Currently, about 90% of the CO<sub>2</sub> network sites also report CH<sub>4</sub> measurements.

#### Remote Sensing

New remote-sensing approaches have emerged such as the international Total Carbon Column



Observing Network (TCCON), which now has six sites in North America among about 20 worldwide. TCCON measurements are made using high-resolution solar-tracking Fourier transform spectrometers (FTSs; Wunch et al., 2011), which are sensitive to the total CO<sub>2</sub> content of the atmospheric column, can provide constraints on large-scale carbon fluxes (Chevallier et al., 2011; Keppel-Aleks et al., 2012), and also help identify biases in satellite-based remote sensors (e.g., Wunch et al., 2016). Since SOCCRI, first-generation CO<sub>2</sub>- and CH<sub>4</sub>-dedicated near-infrared space-based spectrometers have been deployed aboard the Greenhouse Gases Observing Satellite (GOSAT; Japan Aerospace Exploration Agency) and the Orbiting Carbon Observatory-2 (OCO-2; National Aeronautics and Space Administration [NASA]) satellites. Numerous carbon cycle data assimilation systems are attempting to assimilate these CH<sub>4</sub> (GOSAT) and CO<sub>2</sub> (GOSAT and OCO-2) column averages to derive surface fluxes. These efforts are challenged by small but spatially and temporally coherent biases in the data (Basu et al., 2013; Feng et al., 2016; Lindqvist et al., 2015). Estimating emissions anomalies (as opposed to absolute emissions), such as carbon flux variability driven by climate events, has proved to be more successful (Basu et al., 2014; Guerlet et al., 2013; Reuter et al., 2014; Turner et al., 2017). Assimilating column-average GHG data from both ground- and space-based instruments into carbon cycle models is still a rather new activity that requires modifications in traditional atmospheric inverse models. They need to be modified to handle a much larger data volume, extract information from full-column averages, and assimilate retrievals contaminated by coherent biases, which can masquerade as atmospheric gradients arising from surface exchange.

Another remote-sensing approach for CO<sub>2</sub> uses light detection and ranging (LIDAR), which has been deployed at surface sites to measure the mean CO<sub>2</sub> along horizontal paths (Gibert et al., 2008, 2011) and aboard aircraft to measure partial-column integrals (Dobler et al., 2013). Space-based LIDAR total column CO<sub>2</sub> and CH<sub>4</sub> measurements are under

development (Ehret et al., 2008), and a CH<sub>4</sub> system will be deployed on the MERLIN satellite sensor. LIDAR instruments have narrow beams and thus can often obtain data in partly cloudy regions that confound passive sensors. Because they are active, LIDAR instruments can obtain data in the absence of sunlight (at high latitudes or at night). Despite this appealing feature, LIDAR instruments are not yet broadly distributed for atmospheric research.

### Vertical In Situ

Calibrated CO<sub>2</sub> and CH<sub>4</sub> total column values can be measured using *in situ* approaches. The AirCore is a thin steel tube that samples an air profile, typically during a balloon flight (Karion et al., 2010). Profiles (and thus column integrals) of CO<sub>2</sub> and CH<sub>4</sub> (Karion et al., 2010) extend to altitudes that allow sampling of nearly 99% of the atmospheric column of air. In addition to defining the vertical structure of CO<sub>2</sub> and CH<sub>4</sub> in both the troposphere and stratosphere, these data provide calibrated total columns that can be directly compared to remotely sensed soundings from space (e.g., OCO-2 and GOSAT) and the ground (TCCON). Time series of AirCore measurements are being established at Sodankylä, Finland; Orleans, France; Lamont, Oklahoma; and Boulder, Colorado. While not sampling the total column, *in situ* measurements taken aboard light aircraft flying between the surface and 6 to 8 km above sea level also are ongoing. These regular (biweekly to monthly) measurements capture the seasonal and interannual distribution of CO<sub>2</sub>, CH<sub>4</sub>, and other GHGs throughout North America (Sweeney et al., 2015; see Figure 8.2, p. 341). Although the number of air samples collected has not significantly increased since 2007, the number of gases measured has increased from eight to more than 50, including gases like carbonyl sulfide (COS) and the <sup>14</sup>C:C ratio of CO<sub>2</sub> (Δ<sup>14</sup>CO<sub>2</sub>) that are tracers for biogenic and fossil fuel emissions.

### Other Species

Carbon monoxide (CO) retrievals from the Measurements Of Pollution In The Troposphere (MOPITT) and Infrared Atmospheric Sounding Interferometer (IASI) satellite instruments have



been used to constrain biomass burning GHG emissions and help separate intact ecosystem carbon uptake from biomass burning emissions (e.g., van der Laan-Luijkx et al., 2015). Although CO retrievals from these platforms can be biased by 10% or more (De Wachter et al., 2012; Deeter et al., 2016; George et al., 2009), robust signals can still be gleaned since the variation in CO from large biomass burning events can be up to 500% of the background. While not a GHG measurement, solar-induced fluorescence (SIF), a direct by-product of photosynthesis, can be measured from space and is emerging as an important marker of terrestrial gross primary production (Frankenberg et al., 2011; Joiner et al., 2011) and complement to remotely sensed CO<sub>2</sub>. Direct estimation of gross primary production from SIF retrievals remains an area of active research.

### Process Tracers

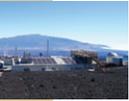
Concentrations and isotopic ratios of carbon cycle process tracers such as COS, CO,  $\Delta^{14}\text{CO}_2$ , halogenated species, <sup>13</sup>CO<sub>2</sub>, <sup>13</sup>CH<sub>4</sub>, propane, and ethane are now being regularly analyzed in North American air and as part of the NOAA tower and aircraft networks and targeted regional and local measurement campaigns. These include programs such as the Mid-Continent Intensive (MCI; NACP) campaign, Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE; NASA), Atmospheric Carbon and Transfer-America (ACT-America) program (NASA), Indianapolis Flux Experiment (INFLUX), and Los Angeles megacities effort (see Section 8.3.2, this page). These process tracers allow for constraints on carbon cycle processes such as photosynthetic CO<sub>2</sub> fixation, fossil fuel emissions, and transport model fidelity.

## 8.3.2 Atmosphere-Based Fluxes from Local to Continental Scales

### Short-Term and Regional to Local Emissions

Since SOCCR1 (CCSP 2007), studies of the carbon cycle have expanded to include regional campaigns designed to understand and quantify ecosystem and anthropogenic sources and sinks in particular regions and seasons. The NACP MCI campaign

intensively sampled the atmosphere above the Midwest agricultural region during 2007 and 2008 and compared sources and sinks derived from atmospheric CO<sub>2</sub> data to those based on bottom-up inventories. The results showed a high degree of convergence between surface fluxes inferred from three atmospheric inversions and bottom-up inventories (Ogle et al., 2015; Schuh et al., 2013). CARVE studied boreal and Arctic ecosystem carbon cycling in Alaska using aircraft and tower CO<sub>2</sub> and CH<sub>4</sub> measurements between 2012 and 2015 (e.g., Chang et al., 2014). One significant finding was that an ensemble of process-based wetland emission models (Melton et al., 2013) systematically underestimated atmospherically constrained CH<sub>4</sub> emissions from tundra ecosystems on Alaska's North Slope (Miller et al., 2016). Recently launched regional studies also should provide new insights into North American carbon cycling. The ACT-America (2015 to 2019) program is designed to explore the structure of GHG distributions within synoptic weather systems and reduce atmospheric transport error in inverse flux estimates using a variety of aircraft observations. The new NASA CARBON Atmospheric Flux Experiment (CARAFE) airborne payload, which is designed for validation of regional carbon flux estimates, was recently deployed to collect airborne eddy covariance measurements for CO<sub>2</sub> and CH<sub>4</sub> (Wolfe et al., 2015). Other studies such as NASA's Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) and Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS), as well as the Texas Air Quality Study (TexAQS), have focused primarily on reactive gas compounds and air quality research but also have measured and interpreted CO<sub>2</sub> and CH<sub>4</sub> data (e.g., Brioude et al., 2012; Townsend-Small et al., 2016; Vay et al., 2011). At much larger scales, the HIAPER (High-Performance Instrumented Airborne Platform for Environmental Research) Pole-to-Pole Observations (HIPPO; 2009 to 2011) and the Atmospheric Tomography Mission (ATom; 2016 to 2018) projects have measured atmospheric trace gas species, including CO<sub>2</sub>



and CH<sub>4</sub>, along north-south transects in the Pacific and Atlantic oceans. These measurements are not significantly sensitive to North American emissions, but they are expected to help constrain large-scale carbon fluxes and atmospheric transport and, by extension, improve understanding of the North American carbon balance.

Many studies at more local scales have been designed to provide constraints on urban CH<sub>4</sub> and CO<sub>2</sub> emissions. A large global trend in urban migration is making cities loci of both emissions and their mitigation, thus driving interest in atmospheric measurement approaches to inform decision making (e.g., Duren and Miller 2012). There have been projects outside of North America (e.g., Bréon et al., 2015; Levin et al., 2011); some North American urban carbon balance studies include those in Indianapolis (INFLUX; Davis et al., 2017), Los Angeles (Feng et al., 2016; Wong et al., 2015; Wunch et al., 2009), Salt Lake City (McKain et al., 2012), and Boston (McKain et al., 2015). In general, these studies have deployed small networks of GHG sensors in and around cities and used the observed gradients, in conjunction with high-resolution atmospheric transport models and bottom-up inventories, to determine urban CH<sub>4</sub> and net CO<sub>2</sub> emissions (fossil and biogenic). Comparisons between atmospherically derived and bottom-up CO<sub>2</sub> emissions show varying degrees of agreement, even in the same city. In Indianapolis, a CO<sub>2</sub> flux calculation using tower observations and a high-resolution (1-km) atmospheric inversion system (Lauvaux et al., 2016) yielded emissions about 20% larger than either the Hestia Project (Gurney et al., 2012; Arizona State University) or Open-source Data Inventory for Anthropogenic CO<sub>2</sub> (ODIAC; Oda and Maksyutov 2011) inventory products, while aircraft mass-balance fluxes (Heimburger et al., 2017) were about 20% lower than the inventories. Indianapolis airborne mass balance CH<sub>4</sub> emissions were about 30% higher than a custom-made urban inventory, and the tower-based inversion suggested CH<sub>4</sub> emissions twice as large as the aircraft mass balance estimate. In Salt Lake City, another atmospheric inversion approach using high-resolution

(1.3-km) meteorology also showed a high level of correspondence with the Vulcan Project. The California Research at the Nexus of Air Quality and Climate Change (CalNex) mission, which sampled CO<sub>2</sub> above Los Angeles, derived emissions 20% to 30% higher than ODIAC and Vulcan (Brioude et al., 2013; Gurney et al., 2012). In the Los Angeles megacities experiment and INFLUX, additional biogenic and anthropogenic process tracers like CO, Δ<sup>14</sup>CO<sub>2</sub>, and numerous hydro- and halocarbons also have been measured (Newman et al., 2016; Turnbull et al., 2015). These data could enable partitioning the net CO<sub>2</sub> signals into anthropogenic and biogenic components.

Local studies also have been undertaken in and around oil and gas extraction fields. Between 2005 and 2016, U.S. natural gas extraction increased by over 38% (U.S. Energy Information Administration, [www.eia.gov/dnav/ng/hist/n9010us2m.htm](http://www.eia.gov/dnav/ng/hist/n9010us2m.htm)). The fraction of CH<sub>4</sub> that leaks during extraction and distribution is highly uncertain and is driving research on both bottom-up and top-down methods. Alvarez et al. (2012) estimated that if this CH<sub>4</sub> leak rate is greater than about 3%, the climate impact of natural gas combustion could equal or exceed that of coal on a per-unit energy basis. Some recent studies of CH<sub>4</sub> emissions from oil and gas production (e.g., Brandt et al., 2014) have found higher emissions compared to estimates from past U.S. Environmental Protection Agency (EPA) inventories. Field studies also have shown considerable variation among regions. For example, Karion et al. (2013) found that emissions from the Uintah Basin in Utah were about 9% of production, while Peischl et al. (2015) found leak rates well under 3% of production for the Haynesville, Fayetteville, and Marcellus shale regions. Based on a variety of studies at scales ranging from individual pieces of equipment to regional scales, Brandt et al. (2014) concluded that leakage rates are unlikely to be large enough to make the climate impact of natural gas as large as that of coal.

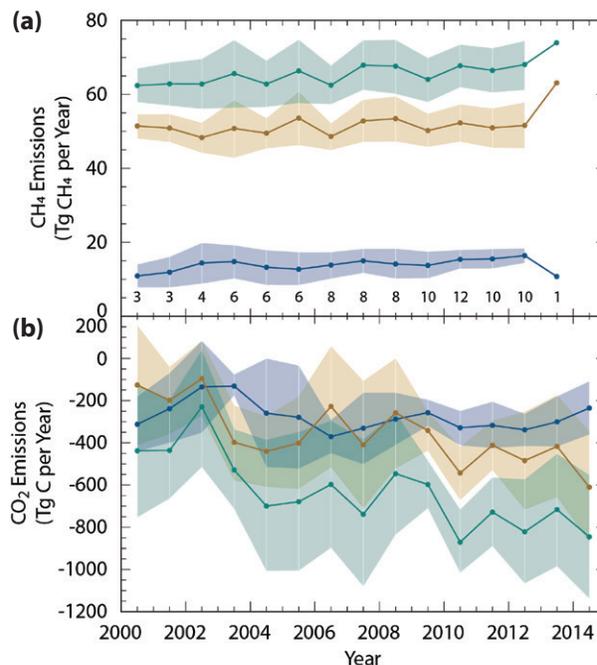
The answer to the question of why field studies suggest higher emissions than official inventories is likely related to the existence of a small number

of “super emitters” that are difficult to capture in inventory-based approaches, but whose atmospheric signatures are often seen in measurements (Brandt et al., 2014; Schwietzke et al., 2017; Kort et al., 2014). For example, Zavala-Araiza et al. (2015) found that half of CH<sub>4</sub> emissions from the Barnett Shale region were due to just 2% of oil and gas facilities, and the study achieved closure within error bounds between atmospheric methods and an inventory product derived from local emissions measurements. Although small in area and duration, these measurement campaigns have provided policy-relevant information using atmospheric CH<sub>4</sub> concentration data.

### Interannual and Continental Emissions

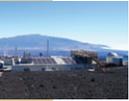
Inverse models such as CarbonTracker have been continuously improved and upgraded to exploit the improved density of atmospheric CO<sub>2</sub> and CH<sub>4</sub> observations (Bruhwiler et al., 2014). Global inversions with regularly updated flux estimates include CarbonTracker (Peters et al., 2007; carbontracker.noaa.gov), the European Union’s Copernicus Atmospheric Monitoring Service (CAMS; atmosphere.copernicus.eu; formerly MACC), Max Planck Institute Jena CarboScope project (Rödenbeck et al., 2003; www.bgc-jena.mpg.de/CarboScope), and CarbonTracker-Europe from Wageningen University (Peters et al., 2010; www.carbontracker.eu). These products constitute the ensemble of inverse models used in this chapter to estimate North American CO<sub>2</sub> fluxes.

Mean annual CO<sub>2</sub> fluxes over North America from this ensemble are shown in Figure 8.3, this page, and listed in Table 8.1, p. 346. These inverse model flux estimates show some level of agreement about mean fluxes and patterns of interannual variability. However, they also manifest notable differences. These differences remain one of the most important indicators of the overall uncertainty in inverse model fluxes. The uncertainty in fluxes derived from inverse models has proven to be a difficult quantity to estimate directly, since those models depend on results from upstream analyses with complicated, unknown uncertainties. For instance,



**Figure 8.3. Inverse Model Estimates of Annual Emissions of (a) Methane (CH<sub>4</sub>) and (b) Nonfossil Fuel Carbon Dioxide (CO<sub>2</sub>) from 2000 to 2014.** Estimates are given in teragrams (Tg) for North America (green), boreal North America (blue), and temperate North America (beige) based on the across-model mean of inverse models. Error bands represent one-sigma across-model spread taken as a proxy for model uncertainty. Methane emissions data are from the Global Carbon Project (GCP) inverse model collection of Saunio et al. (2016), with the number of models contributing to each annual mean shown in black. Carbon dioxide emissions are the across-model mean of the four inverse models collected for this report. Negative emissions represent a sink.

some of the overall difference in inverse model fluxes can be attributed to differing atmospheric transport among the models, which assume that the winds and diffusive mixing of the transport model are unbiased and subject only to random error. Another element of overall uncertainty comes from the structure of the flux estimation scheme in each inverse model. This structure includes the choice of prior emissions from the burning of fossil fuels, terrestrial biosphere, and the ocean used in the model. The interpretation of results from inverse models is further complicated by the fact that these



**Table 8.1. Estimates of Annual, North American, Land Biosphere Carbon Dioxide (CO<sub>2</sub>) Fluxes (Including Fire) Derived from Atmospheric CO<sub>2</sub> Measurements Using Inverse Models and the U.S. Environmental Protection Agency (EPA) Inventory over the Period 2004 to 2013**

	CT2015	CAMS <sup>a</sup>	CTE2015	CarboScope <sup>b</sup>	Inverse Models	EPA	Fossil Fuel Emissions
Boreal North America	-160 ± 77	-356 ± 61	-302 ± 50	-407 ± 64	-306 ± 43		30 ± 1
Temperate North America	-352 ± 111	-602 ± 95	-252 ± 126	-365 ± 109	-393 ± 67	-202 ± 5 <sup>c</sup>	1744 ± 37
North America	-511 ± 106	-959 ± 117	-555 ± 147	-773 ± 107	-699 ± 82		1774 ± 24

Emissions in teragrams of carbon (Tg C) per year are listed for the Atmospheric Tracer Transport Model Intercomparison Project's (TransCom) temperate and boreal North American regions (Gurney et al., 2002). The "inverse models" column averages across the four inverse models (CarbonTracker [CT], Copernicus Atmospheric Monitoring Service [CAMS], CarbonTracker-Europe [CTE], and CarboScope) and represents the best estimate from this ensemble. Fossil fuel emissions are derived from Boden et al. (2017). Values reported are the 2004 to 2013 mean plus or minus a measure of interannual and across-model variability (twice the standard error of the mean of annual emissions). Negative emissions represent a sink.

#### Notes

a) Version v15r4, atmosphere.copernicus.eu.

b) Version v3.8.

c) U.S. EPA (2017) estimates correspond to "managed lands" in the United States, which largely corresponds to the TransCom temperate North American region.

models retrieve spatiotemporal patterns of CO<sub>2</sub> and CH<sub>4</sub> fluxes that do not necessarily correspond with patterns expected from differing theories about ecosystem carbon exchange; therefore, they do not map directly onto improvements in process knowledge. Despite these limitations, inverse model results are important because their net carbon flux estimates are by construction consistent with atmospheric data constraints. Ensembles of inverse models using different transport, structure, data inputs, and priors are particularly useful since they mitigate some of these limitations.

Previous comparisons of inverse models such as Baker et al. (2006) and Peylin et al. (2013) indicated that, while each inversion manifests a different long-term mean flux estimate, the patterns of interannual variability tend to have better agreement. There is some indication of interannual variation coherence in the present collection of models, but with some significant disagreement, mainly from the Jena CarboScope model. Averaging across the

inversions, the land biosphere sink in North America, including fire emissions, averaged over 2004 to 2013 is 699 ± 82 Tg C per year (mean ± two standard errors of the mean of the interannual and intermodel variability). This sink offsets about 39% of the fossil fuel emissions of 1,774 ± 24 Tg C per year for the same geographic area, although 98% of these anthropogenic emissions come from just the temperate North American region. Disagreement remains among these inversions about the average size of the North American sink, but they all estimate significant interannual variability in that sink. Over the temperate North American region, these inverse models estimate interannual variability (one sigma) of between 163 and 277 Tg C per year, equivalent to 45% to 83% of each model's mean flux.

The level of interannual variability from inverse models stands in stark contrast to the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks, prepared by the U.S. EPA. EPA's U.S. GHG inventory estimates land use, land-use change, and

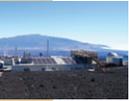


forestry (LULUCF) sector emissions on managed lands. Managed lands represent about 95% of total U.S. land cover and more than 99% of the conterminous United States, which corresponds well to the net biosphere fluxes estimated by inversion models for temperate North America. EPA's LULUCF CO<sub>2</sub> sink estimate has a 2004 to 2013 mean of  $202 \pm 5$  Tg C per year (U.S. EPA 2017; mean plus or minus two standard errors of the mean). The small interannual variability in the EPA inventory of just 5 Tg C per year stands in contrast to all the inverse models. This low apparent variability may arise from the historical 5- to 14-year frequency at which U.S. Forest Service Forest Inventory and Analysis (FIA) plots have been resampled. Comparing the interannual variability of inventories and inversions is inherently difficult due to the mismatch in their temporal sensitivities.

Various estimates of North American surface CO<sub>2</sub> emissions were collected as part of the recent NACP regional interim synthesis (Hayes et al., 2012; Huntzinger et al., 2012) and REgional Carbon Cycle Assessment and Processes (RECCAP) effort (Canadell et al., 2011; King et al., 2015). The RECCAP North America study included a suite of inverse models collected by Peylin et al. (2013) with a 2000 to 2009 mean CO<sub>2</sub> sink of  $890 \pm 400$  Tg C per year (mean and one sigma standard deviation), implying a larger sink than either inventory (270 Tg C per year) or terrestrial biosphere model ( $359 \pm 111$  Tg C per year) estimates (King et al., 2015). The current suite of inverse models collected for this report (see Table 8.1, p. 346) suggests North American biosphere emissions of  $699 \pm 82$  Tg C per year averaged over 2000 to 2014. The models collected for this chapter also supplied results from their earlier versions to the RECCAP ensemble of Peylin et al. (2013). That report showed a wide range of North American flux estimates, but the subset of models used in this chapter all manifested sinks smaller than 500 Tg C per year for North America over the reporting period 2001 to 2004, whereas the other models all estimated greater sinks between about 500 and 1,500 Tg C per year.

The North American sink estimated from the suite of inverse models collected for this report agrees well with previous bottom-up estimates. SOCCR1 (Pacala et al., 2007) reported a sink of  $666 \pm 250$  Tg C per year for 2003. This estimate was derived from bottom-up inventories and models and did not include information from atmospheric inverse models. Hayes et al. (2012) attempted to reconcile net biosphere emissions estimates from inventories, terrestrial biosphere models, and atmospheric inverse models averaged over 2000 to 2006 for North America. That study found a sink of 511 Tg C per year simulated by terrestrial biosphere models and an inventory-based sink estimate of 327 Tg C per year (with an estimate of additional noninventoried fluxes that brings the total sink estimate to 564 Tg C per year). The collection of inverse models used in that study manifested significantly larger sinks (981 Tg C per year) than the current collection. See Ch. 2: The North American Carbon Budget, p. 71, for an assessment of the overall agreement of these various estimates of North American surface CO<sub>2</sub> exchange with the atmosphere.

The use of regional models of CO<sub>2</sub> and CH<sub>4</sub> has become more common since SOCCR1. These models have focused, for example, on continental-scale processes (Butler et al., 2010; Gourdji et al., 2012; Schuh et al., 2010) or at the scale of the mid-continent (Lauvaux et al., 2012b; Schuh et al., 2013). Regional model CO<sub>2</sub> flux estimates for North America so far have been published for periods of up to 1 year, with multi-year analyses only available from global inversion approaches. One prominent result from regional inverse CO<sub>2</sub> studies is the sensitivity of the annual net CO<sub>2</sub> flux to defining the inflow of atmospheric CO<sub>2</sub> into the study region (Gourdji et al., 2012; Schuh et al., 2010). Lauvaux et al. (2012b) demonstrated that this sensitivity could be minimized with observations at the inflow boundaries. This finding highlights the importance of global-scale measurement networks and carbon reanalysis systems for understanding North American carbon fluxes. More recently, CH<sub>4</sub> has received more attention with regional inversions for the continent (Kort et al.,



2008; Miller et al., 2013), California (Jeong et al., 2013), and Alaska (Chang et al., 2014; Miller et al., 2016). Additional uncertainties in inverse modeling approaches arise from sparse data coverage. When the observational network is not strongly sensitive to particular land regions, inverse modeling systems must make assumptions about spatial and temporal patterns of emissions. As with the issue of boundary inflow, mitigating this sensitivity necessitates building a denser, intercalibrated measurement network.

## 8.4 Indicators, Trends, and Feedbacks

Atmospheric CH<sub>4</sub> and CO<sub>2</sub> levels continue to increase. In the case of CO<sub>2</sub>, this increase is unambiguously a result of anthropogenic emissions, primarily from fossil fuel combustion, with North America accounting for about 20% of global emissions. The recent rise in global CH<sub>4</sub> concentrations (see Figure 8.1, p. 339), on the other hand, has been attributed primarily to biological, not fossil, processes on the basis of a concomitant decrease in the global mean <sup>13</sup>C:<sup>12</sup>C ratio and the tropical origin of the increase (Nisbet et al., 2016; Schaefer et al., 2016; Schwietzke et al., 2016). Two recent analyses render the causes of recent CH<sub>4</sub> growth rate changes less clear. First, studies have pointed out that the tropospheric CH<sub>4</sub> sink may not have been constant over recent years as had been assumed (Rigby et al., 2017; Turner et al., 2017). Secondly, Worden et al. (2017) suggest that atmospheric δ<sup>13</sup>C of CH<sub>4</sub> may have decreased because of less biomass burning, thus allowing for an increase in isotopically heavier fossil fuel CH<sub>4</sub> sources. Nonetheless, these results mostly pertain to the global mean and do not directly bear on potential trends in North American emissions. Despite the recent increase in oil and gas production due to new extraction technologies, both inventories and atmospheric inversions do not reveal an increase in North American CH<sub>4</sub> emissions (Bruhwiler et al., 2014; Miller et al., 2013; U.S. EPA 2016; see Figure 8.3, p. 345). Normalizing CH<sub>4</sub> and CO<sub>2</sub> emissions using a 100-year global warming potential (GWP) indicates that U.S. radiative forcing from CH<sub>4</sub> emissions from 2000 to 2013 equates to just

13% of that from CO<sub>2</sub>. Changes in U.S., Canadian, and Mexican energy systems will affect the atmospheric trends of anthropogenic CO<sub>2</sub> and CH<sub>4</sub>, but U.S. GHG emissions currently are dominated by CO<sub>2</sub> and are likely to remain so for the foreseeable future.

Much less certain than anthropogenic CO<sub>2</sub> sources is the balance of biogenic sources (respiration and fire) and sinks (photosynthesis). There is general agreement that the terrestrial biosphere of the United States, and North America as a whole, acts as a CO<sub>2</sub> sink (see Figure 8.3, p. 345, and Table 8.1, p. 346; Hayes et al., 2012; King et al., 2015), but there is substantial uncertainty about the location of and reasons for the sinks. There is evidence that their interannual variability is driven largely by climatic factors. For example, Peters et al. (2007) presented evidence for a direct effect of drought on the North American sink. Understanding the spatial and temporal variability of sinks is critical, because positive feedbacks between net ecosystem CO<sub>2</sub> exchange and climate represent a first-order uncertainty in climate projections (Bodman et al., 2013; Booth et al., 2012; Friedlingstein et al., 2006, 2014; Huntingford et al., 2009; Wenzel et al., 2014; Wieder et al., 2015). At hemispheric and global scales, atmospheric CO<sub>2</sub> data have proved to be a powerful constraint on the representation of the carbon cycle (including, to some measure, feedbacks) in climate models (e.g., Cox et al., 2013; Graven et al., 2013; Keppel-Aleks et al., 2013; Randerson et al., 2009). The present generation of global atmospheric inverse models is limited by the accuracy and resolution (generally about 1° × 1°) of meteorological transport, availability and accuracy of prior flux emissions, uncertainty about the spatial coherence of prior flux errors, and the limited set of observation sites shown in Figure 8.2, p. 341. Together, these limitations mean that, at present, global atmospheric inverse models cannot unambiguously resolve source-sink patterns below the scale of 5 to 10 million km<sup>2</sup>. A new generation of regional and local models using much higher resolution meteorology (e.g., approaching the approximately 1- to 4-km resolution used by Lauvaux et al. [2016] and McKain et al. [2015]) will be more



capable of assimilating data from the sites in Figure 8.2, p. 341. Without quantitative knowledge of the spatial structure of flux uncertainties (Cooley et al., 2012; Ogle et al., 2015) and atmospheric transport errors (Díaz Isaac et al., 2014; Lauvaux and Davis 2014), these high-resolution inverse systems will have limited ability to determine the spatial structure of fluxes (Lauvaux et al., 2012a, 2016). Nonetheless, these improved inversion systems should enable better understanding of the climate-carbon relationship in North America.

## 8.5 Societal Drivers, Impacts, and Carbon Management

In a potential future when carbon emissions have a significant economic cost and international agreements to control emissions are in place, verifying claims of emissions mitigation and assessing the efficacy of mitigation strategies will be necessary. In addition to international agreements, 18 states have plans in place to reduce GHG emissions. Bottom-up methods based on economic, agricultural, and forest inventories provide much of the basis for these calculations. These methods are susceptible to systematic errors, including incomplete sectoral coverage, misreporting, and the use of uncertain emissions factors. Top-down methods derive emissions budgets consistent with atmospheric concentrations of GHGs, but they also contain systematic errors resulting from imperfect knowledge of atmospheric transport and lack of observations. Although these uncertainties place limits on the accuracy of top-down emissions estimates, atmospheric data still provide strong constraints on GHG emissions from local to global scales (e.g., Levin et al., 2010). As shown by the example of Brandt et al. (2014), natural gas super emitters can be localized from *in situ* observations even when they have not previously been identified by inventories. As described in this chapter, both existing and new technologies can provide independent and complementary information and help reconcile emissions estimates from the bottom-up and top-down approaches. From a carbon management and decision perspective, collecting and utilizing information from atmospheric data

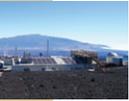
could provide additional information in regions and sectors where uncertainties in bottom-up inventories are large. Top-down emissions estimates can be produced with low latency and with robust uncertainty quantification. Together, these two methods can provide robust observational constraints on emissions at a variety of scales.

## 8.6 Synthesis, Knowledge Gaps, and Outlook

### 8.6.1 Findings from Atmospheric Inversions and Related Analyses

The present collection of atmospheric CO<sub>2</sub> inversions shows no clear trend in the boreal North American sink, but it does suggest the possibility of an increasing sink in temperate latitudes. A more robust feature of atmospheric inversions is that they show that the North American CO<sub>2</sub> sink is more highly variable and sensitive to drought and temperature stress than bottom-up biosphere models (King et al., 2015; Peters et al., 2007). Inversions also produce a larger mean sink and a deeper annual cycle than terrestrial biosphere models. Significant uncertainty remains about the magnitude of the mean North American carbon sink, in part because models disagree about the partitioning of the net sink between northern and tropical land regions. The mechanisms behind the land sink cannot be understood fully without more agreement on its location. Notably, distinguishing between a potentially short-lived sink due to recovery from past land-use practices (mainly a temperate Northern Hemisphere phenomenon) and a longer-term sink due to CO<sub>2</sub> fertilization remains elusive. Moreover, the role of carbon-climate feedback processes in North America, both negative (e.g., extended growing seasons and tree-line migration) and positive (e.g., permafrost carbon release and insect outbreaks), is poorly understood at present. Atmospheric measurements can impose significant constraints on these processes (e.g., Sweeney et al., 2015), and continued and expanded measurements, especially in sensitive Arctic and boreal regions, will be critical moving forward.

Inventories suggest that fossil fuel CO<sub>2</sub> emissions are stabilizing and even decreasing for certain



regions and sectors of the global and North American economy. This finding is difficult to verify given the *ad hoc* nature of the GHG observation network, lack of integration among programs, and sparse measurements of anthropogenic emissions tracers such as  $\Delta^{14}\text{CO}_2$  and CO.

Individual atmospheric  $\text{CH}_4$  inversions consistently show no trend and little interannual variability in total  $\text{CH}_4$  emissions (natural and anthropogenic) for both the temperate (largely the United States) and boreal regions and the continent as a whole (see Figure 8.3, p. 345). These results suggest that North American emissions have not contributed significantly to the global upward trend that started in 2007. Increasing oil and gas production in North America could result in increased  $\text{CH}_4$  emissions, a result apparently confirmed by Turner et al. (2016) on the basis of comparing inverse model estimates from different time periods. This conclusion has been called into question by Bruhwiler et al. (2017), who argue that robust trend detection is limited by interannual variability, the sparse *in situ* measurement network, and biased satellite  $\text{CH}_4$  retrievals. Recent increases in atmospheric ethane and propane suggest increased  $\text{CH}_4$  emissions from fossil fuel production, although there is uncertainty in this conclusion due to poorly quantified emissions ratios (Helmig et al., 2016). As with  $\text{CO}_2$  though, little reliable spatial information is available from the current suite of  $\text{CH}_4$  inverse models. This limitation hampers attribution to specific mechanisms including  $\text{CH}_4$ -climate feedbacks, especially in the boreal zone where permafrost degradation plays a key role in changing  $\text{CH}_4$  and  $\text{CO}_2$  fluxes (McGuire et al., 2016; see also Ch. 11: Arctic and Boreal Carbon, p. 428).

## 8.6.2 Future Atmospheric Measurement Challenges and Strategies for North America

### Compatibility Among Networks

As the community expands research into new domains and with new measurement strategies, new challenges are emerging. Compatibility of measurements among existing and future networks is a concern, as there is ample history of calibration

difficulties from the decades of *in situ* measurement experience (e.g., Brailsford et al., 2012). This challenge is being addressed by careful attention to calibration and participation in laboratory and field intercomparison activities (Masarie et al., 2011; [www.esrl.noaa.gov/gmd/ccgg/wmorr/](http://www.esrl.noaa.gov/gmd/ccgg/wmorr/)). Much more challenging is linking ground- and space-based remote-sensing measurements to each other and to the calibrated *in situ* networks. Concentrations derived from any remote-sensing gas measurement, whether ground- or space-based, cannot be formally calibrated because the measurement instrument cannot be “challenged” by a reference sample with a known concentration. Thus, identification and correction of biases remain a significant challenge. With the OCO-2 and GOSAT programs, the primary strategy has been to compare the satellite-based retrievals with TCCON retrievals. The TCCON retrievals of column  $\text{CO}_2$  are themselves remote-sensing products that have been statistically linked to the World Meteorological Organization  $\text{CO}_2$  calibration scale using aircraft *in situ* partial column  $\text{CO}_2$  and  $\text{CH}_4$  extrapolated to the top of the atmosphere (Wunch et al., 2011). This linkage remains uncertain due to the limited number of *in situ* profiles used and their limited maximum altitude. A limited number of nearly total column AirCore (Karion et al., 2010) measurements also have been compared with TCCON columns.

Bias correction of satellite retrievals remains challenging due to the limited number of TCCON stations (currently less than 20) and because estimates of the TCCON site-to-site bias of 0.4 ppm (one-sigma; Wunch et al., 2016) are significant for carbon cycle studies. As an example of the importance of small biases, Reuter et al. (2014) demonstrated that a gradient of 0.5 ppm in column  $\text{CO}_2$  across Europe was associated with a change in flux over that region of about  $-500$  Tg C per year. This increased sink over Europe using a regional model is consistent with the inversion intercomparison of Houweling et al. (2015), who found that assimilating GOSAT column  $\text{CO}_2$  retrievals in global inversion models caused an increase of about 700 Tg C per year in the European sink, with a compensating increase



in the northern Africa source of about 900 Tg C per year. These shifts in emissions were associated with degraded agreement with unassimilated *in situ* observations from both surface observation sites and aircraft campaigns. For comparison, the *in situ* assimilation models collected for this chapter estimate a modest sink of  $219 \pm 405$  Tg C per year in Europe and a negligible source of  $13 \pm 281$  Tg C per year in northern Africa over the 2004 to 2013 period. These uncertainties, which comprise both interannual variability and intermodel differences in the inversions, are relatively large but still appear inconsistent with the GOSAT-driven flux increments reported in Houweling et al. (2015). In the relatively short time that GOSAT and OCO-2 have been collecting data, significant progress has been made in identifying and correcting biases in those datasets. Progress also is needed in understanding the time and space scales of remote-sensing data least susceptible to bias and how to assimilate these retrievals jointly with *in situ* data having less bias. Moving forward, more measurements will be key, including expansion of AirCore (Karion et al., 2010) and commercial aircraft observations (Basu et al., 2014) that will enable better assessment and utilization of both ground- and space-based total column CO<sub>2</sub> and CH<sub>4</sub> remote-sensing data.

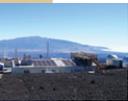
### Next-Generation Measurements

Atmospheric measurements will play an important role in addressing these critical questions on the present and future state of both anthropogenic and biogenic components of the North American carbon cycle. The following is a list of potential, yet achievable, atmospheric measurement approaches that could dramatically change the current view of the North American (and global) carbon cycle.

**A. Commercial Aircraft CO<sub>2</sub> and CH<sub>4</sub> Observations.** The Comprehensive Observation Network for Trace gases by Airliner (CONTRAIL) program has measured GHGs from commercial aircraft for nearly two decades (Matsueda et al., 2008). A similar European effort, In-service Aircraft for a Global Observing System (IAGOS) project (Filges et al., 2015), is not yet fully

operational for GHG measurements. The technology exists for unattended, high-accuracy airborne CO<sub>2</sub> and CH<sub>4</sub> measurements (Karion et al., 2013), and deploying instruments aboard 40 domestic U.S. commercial aircraft could result in approximately 500 vertical profiles per day, radically changing CO<sub>2</sub> and CH<sub>4</sub> data density over North America.

- B. Greatly Expanded  $\Delta^{14}\text{CO}_2$  Measurements.** Recently, Basu et al. (2016) demonstrated that expanding the U.S. network of  $\Delta^{14}\text{CO}_2$  measurements from about 800 per year to 5,000 per year, as recommended by the U.S. National Research Council (Pacala et al., 2010), could allow for atmospherically based determination of U.S. fossil fuel CO<sub>2</sub> emissions to within 5%, complementing official U.S. EPA inventory-based estimates. In addition to  $^{14}\text{CO}_2$ , other tracers such as CO, non-methane hydrocarbons, halogenated species, and  $^{14}\text{CH}_4$  (for fossil CH<sub>4</sub> identification) can serve as powerful constraints on emissions, both in total and by sector.
- C. Upcoming Satellite-Based CO<sub>2</sub> and CH<sub>4</sub> Sensors.** These sensors, including GOSAT-2, OCO-3, TanSat (China), Geostationary Carbon Cycle Observatory (GeoCARB; NASA), MERLIN (France and Germany), TROPOMI (European Space Agency), and others (Ciais et al., 2014) likely will enable dramatically increased spatial coverage of total column CO<sub>2</sub>, CH<sub>4</sub>, and other gases. For the utility of these data to be maximized, existing challenges associated with aerosols, characterization of the ocean and land surface, clouds, daylight, and, more generally, the linkage to formal gas concentration scales must be overcome. GOSAT and OCO-2, and particularly their planned successors, also will yield information on chlorophyll fluorescence (SIF), which has potential as a marker of time and space patterns of plant photosynthesis.
- D. NEON.** If built out as planned, NEON (National Science Foundation) will provide calibrated CO<sub>2</sub> measurements on towers over a variety of North American biomes that will add



significantly to the North American CO<sub>2</sub> observational dataset.

- E. Additional Gas Tracers.** As with anthropogenic ancillary tracers (see B), numerous gases can serve as tracers of terrestrial ecosystem processes. Gross primary production fluxes are closely linked to atmospheric gradients in COS and  $\Delta^{17}\text{O}$  (anomalies in the  $^{18}\text{O}:^{17}\text{O}$  ratio of CO<sub>2</sub>; e.g., Campbell et al., 2008; Thiemens et al., 2014). Atmospheric  $\delta^{13}\text{CO}_2$  is sensitive to the impact of regional-scale moisture stress on terrestrial photosynthesis (Ballantyne et al., 2010) and can distinguish C<sub>3</sub> and C<sub>4</sub> plant productivity. Schwietzke et al. (2016) showed the potential for  $\delta^{13}\text{CH}_4$  observations to distinguish fossil fuel CH<sub>4</sub> emissions from other sources. Measurements of the  $\delta^{18}\text{O}$  of CO<sub>2</sub> reflect both biospheric processes and changes in the hydrological cycle (Ciais et al., 1997; Flanagan et al., 1997; Miller et al., 1999).
- F. Measurements to Improve Atmospheric Transport Simulation.** Such measurements are critical for fully extracting the information content of atmospheric CO<sub>2</sub> and CH<sub>4</sub> data. Better understanding and parameterizing of atmospheric transport are critical. Near-surface GHG

concentrations are a sensitive function of the planetary boundary-layer mixing height, wind speed, and wind direction. Measurements of the vertical wind structure and boundary-layer depth using rawinsonde, LIDAR, and radar, and assimilating these data into atmospheric transport models, can improve atmospheric transport significantly (Deng et al., 2017). Simulated CO<sub>2</sub> transport is sensitive to boundary-layer mixing, convective cloud transport, synoptic weather patterns, and the surface energy balance, all of which can be difficult to simulate with the high accuracy and precision required for atmospheric inversions. Fortunately, decades of weather forecasting research provide a strong foundation for improving the meteorological reanalyses used in atmospheric inversions. Observational programs that merge meteorological measurements with high-density GHG data (e.g., ACT-America) are aimed at advancing this aspect of atmospheric inverse modeling. In addition, measurements of tracers such as water vapor isotopic ratios, sulfur hexafluoride (SF<sub>6</sub>), and even  $^{14}\text{CO}_2$ , where emissions are relatively well known (Turnbull et al., 2008), also can constrain simulated transport (Denning et al., 1999; Patra et al., 2011; Peters et al., 2004).



## SUPPORTING EVIDENCE

### KEY FINDING 1

Global concentrations of carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) have increased almost linearly since the *First State of the Carbon Cycle Report* (CCSP 2007; see Figure 8.1, p. 339). Over the period 2004 to 2013, global growth rates estimated from the National Oceanic and Atmospheric Administration's (NOAA) marine boundary layer network average  $2.0 \pm 0.1$  parts per million (ppm) per year for CO<sub>2</sub> and  $3.8 \pm 0.5$  parts per billion (ppb) per year for CH<sub>4</sub>. Global mean CO<sub>2</sub> abundance as of 2013 was 395 ppm (compared to preindustrial levels of about 280 ppm), and CH<sub>4</sub> stands at more than 1,810 ppb (compared to preindustrial levels of about 720 ppb); (*very high confidence*).

#### **Description of evidence base**

Global mean atmospheric growth rates and abundances of CO<sub>2</sub> and CH<sub>4</sub> are derived from publicly available tables on NOAA websites: 1) [www.esrl.noaa.gov/gmd/ccgg/trends/global.html](http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html) and 2) [www.esrl.noaa.gov/gmd/ccgg/trends\\_ch4/](http://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/).

#### **Major uncertainties**

The averages were calculated from the regularly updated marine boundary layer sites of NOAA's Global Greenhouse Gas Reference Network. These averages are not associated with any recent literature. The methodology used to construct the global "surfaces" from which the global averages are computed is described in Masarie and Tans (1995). The uncertainties originate primarily from the incomplete sampling of the marine boundary layer by the NOAA network and the uncertainty associated with smoothing the raw data prior to creating the global surface. Measurement uncertainty of CO<sub>2</sub> and CH<sub>4</sub> is a minor component. Uncertainty calculations are described in detail at: [www.esrl.noaa.gov/gmd/ccgg/mb/mb.html](http://www.esrl.noaa.gov/gmd/ccgg/mb/mb.html). While the atmospheric CO<sub>2</sub> growth rate is relatively stable, there is strong decadal and interannual variability of CH<sub>4</sub> emissions, making computation of an average inherently sensitive to the choice of time period. For instance, the CH<sub>4</sub> growth rate averaged over 1997 to 2006 was 2.8 ppb per year, whereas over 2007 to 2015, it was instead 7.0 ppb per year.

#### **Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement**

NOAA data are the gold standard for determining global growth rates and abundances because of extensive global coverage and high internal network compatibility, including high measurement precision. The trends and growth rates also agree well with estimates from other laboratories.

#### **Summary sentence or paragraph that integrates the above information**

NOAA CO<sub>2</sub> and CH<sub>4</sub> trends and abundances are publicly available, fully traceable, and represent the most comprehensive description of global CO<sub>2</sub> and CH<sub>4</sub>.

### KEY FINDING 2

Inverse model analyses of atmospheric CO<sub>2</sub> data suggest substantial interannual variability in net carbon uptake over North America. Over the period 2004 to 2013, North American fossil fuel emissions from inventories average  $1,774 \pm 24$  teragrams of carbon (Tg C) per year, partially offset by the land carbon sink of  $699 \pm 82$  Tg C year. Additionally, inversion models suggest a trend



toward an increasing sink during the period 2004 to 2013. These results contrast with the U.S. land sink estimates reported to the United Nations Framework Convention on Climate Change, which are smaller and show very little trend or interannual variability.

#### ***Description of evidence base***

Fossil fuel emissions are from Carbon Dioxide Information Analysis Center (CDIAC) estimates (available from the U.S. Department of Energy's Environmental Systems Science Data Infrastructure for a Virtual Ecosystem [ESS-DIVE] data archive, [ess-dive.lbl.gov](http://ess-dive.lbl.gov)). The land carbon sink is based on the 10-year average of North American annual fluxes from four global inverse models, specified in the text. The error reported is twice the standard error of the mean of the 10 years and for the four models and mostly represents the amount of interannual variability. The evidence for a trend is based on a linear least-squares regression. The comparison of variability with the U.S. Environmental Protection Agency's (EPA) estimate of the U.S. land sink is based on EPA data accessed at [www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2015](http://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2015).

#### ***Major uncertainties***

Fossil fuel emissions uncertainty is very low (see Appendix E: Fossil Fuel Emissions Estimates for North America, p. 839). Long-term means of CO<sub>2</sub> sources and sinks derived from a given inverse model are highly uncertain. However, the interannual variability of fluxes from different models tends to agree well, suggesting lower uncertainty. EPA land flux estimates may not exhibit enough variability due to the U.S. Forest Service methodology, upon which EPA's estimates are largely based.

#### ***Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement***

Fossil fuel uncertainty at the national, annual scale has the smallest uncertainty because it can be constrained by highly accurate information on imports and exports and internal usage. Inverse model-based estimates of CO<sub>2</sub> sources and sinks contain numerous random and systematic errors including biases associated with wind fields and parameterization of vertical mixing. Because models exhibit different mean atmospheric transport, their long-term average fluxes can differ significantly. However, the interannual variability of fluxes among inverse models is much more similar, meaning that the difference between the inverse model and EPA flux variability is likely to be robust.

#### ***Estimated likelihood of impact or consequence, including short description of basis of estimate***

The contrast between variability exhibited in the inverse model and the EPA estimates of land sink variability could cause EPA to reexamine its methodologies. Additionally, the emerging evidence that the North American CO<sub>2</sub> sink is growing also could spur research in the "bottom-up" community and impact policy decisions.

#### ***Summary sentence or paragraph that integrates the above information***

Regularly produced inverse modeling estimates of CO<sub>2</sub> sources and sinks over North America are beginning to provide valuable information at least on interannual variability of terrestrial ecosystem fluxes.



### KEY FINDING 3

During most of the study period covered by the *Second State of the Carbon Cycle Report* (2004 to 2012), inverse model analyses of atmospheric CH<sub>4</sub> data show minimal interannual variability in emissions and no robust evidence of trends in either temperate or boreal regions. The absence of a trend in North American CH<sub>4</sub> emissions contrasts starkly with global emissions, which show significant growth since 2007. Methane emissions for North America over the period 2004 to 2009 estimated from six inverse models average  $66 \pm 2$  Tg CH<sub>4</sub> per year. Over the same period, EPA-reported CH<sub>4</sub> emissions equate to a climate impact of 13% of CO<sub>2</sub> emissions, given a 100-year time horizon.

#### **Description of evidence base**

The conclusions of minimal interannual variability (standard deviation), trend (slope and its uncertainty), and mean flux are all based on fluxes from 14 inverse models used in the global CH<sub>4</sub> budget analysis of the Global Carbon Project (Saunio et al., 2016). The 13% ratio of CH<sub>4</sub> to CO<sub>2</sub> warming impact is based on EPA CH<sub>4</sub> and CO<sub>2</sub> emission estimates using a 100-year global warming potential (GWP) value of 28.

#### **Major uncertainties**

Total CH<sub>4</sub> emissions for North America include the inversely derived value of 60 Tg CH<sub>4</sub> per year and the EPA anthropogenic emissions estimate for the United States, which would impact the 13% ratio. Inverse models are subject to poorly known uncertainties stemming from the use of biased priors, imperfect models of atmospheric transport, and the sparse network of *in situ* measurements.

#### **Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement**

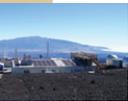
Total emissions have a high uncertainty (not reflected in the variability value stated in the Key Finding); note that EPA does not provide an uncertainty for its estimate. The absence of any trend has higher confidence, because numerous models with different methodologies contributed to this finding. However, the models used in the comparison did not uniformly cover the 2000 to 2013 period, making the conclusion less robust than that for CO<sub>2</sub>. On the other hand, the smaller variability relative to CO<sub>2</sub> is consistent across models and is more robust. The 13% value is uncertain because of EPA's CH<sub>4</sub> emissions estimate and, to a lesser extent, the GWP uncertainty.

#### **Estimated likelihood of impact or consequence, including short description of basis of estimate**

The finding that CH<sub>4</sub> is unlikely to have a temperate North American trend different from zero is significant, because there is great interest in the cumulative radiative forcing impact of CH<sub>4</sub> emissions from the oil and gas sector. Moreover, while not a new finding, the simple calculation of CH<sub>4</sub> having only 13% of the warming impact as CO<sub>2</sub> should remind policymakers and scientists that CO<sub>2</sub> emissions are substantially more important.

#### **Summary sentence or paragraph that integrates the above information**

The global and North American emissions were derived using atmospheric CH<sub>4</sub> data assimilated in a wide variety of CH<sub>4</sub> inverse models using both *in situ* and remote-sensing data. Although a consistent picture is emerging, the results are more uncertain than those for CO<sub>2</sub>, because estimates are not produced regularly over consistent timescales.

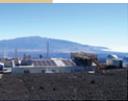


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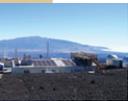
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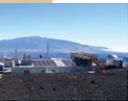
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